Rolling Airframe Missile: Development, Test, Evaluation, and Integration

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The Rolling Airframe Missile (RAM) Guided Missile Weapon System is a short- to moderate-range surface-to-air weapon system for ownship defense against Anti-Ship Cruise Missiles. Developed under a cooperative program between the United States and Germany, the original version used dual-mode guidance with initial passive radio-frequency (RF) guidance that transitioned to passive infrared (IR) guidance for accurate terminal homing. Subsequently, a mode using IR all-the-way guidance was added. APL has been heavily involved in the RAM program from its inception in the early 1970s. The Laboratory conceived of using passive RF guidance and its implementation in a rolling airframe, which allowed an innovative and simplified design that results in highly accurate intercepts. Combining passive RF and IR guidance modes was a collaborative effort between APL and General Dynamics, Pomona. APL continues to support the RAM program by developing both IR measuring devices and background simulations, conducting predictive analyses, and providing combat system support.

INTRODUCTION

There are well over 100,000 anti-ship missiles in the world's inventory today, posing a serious threat to all naval vessels. Guaranteed destruction of a large raid is the only means to ensure ship survival. The Rolling Airframe Missile (RAM) Guided Missile Weapon System (GMWS) is the world's most modern ship self-defense weapon and has been specifically designed to provide exceptional protection for ships of all sizes. RAM is currently installed or planned for installation on over 80 U.S. Navy and 28 German Navy ships.

RAM is a supersonic, lightweight, quick-reaction, fire-and-forget missile designed to destroy anti-ship missiles. Its autonomous dual-mode passive radio-frequency (RF) and infrared (IR) guidance design, requiring no shipboard support after missile launch, uniquely provides high firepower capability for engaging multiple threats simultaneously.

The Mk 44 Guided Missile Round Pack, coupled with the 21-cell Mk 49 Guided Missile Launching System (GMLS), comprise the Mk 31 GMWS. The system has been designed for flexibility in ships' integration, with no "dedicated" sensors required. A wide variety of existing ship sensors can readily provide the target and pointing information needed to engage the anti-ship threat.

The RAM missile has been fired in over 150 flight tests to date, with a success rate of greater than 95%. This extremely high reliability is the culmination of years of development, testing, and design improvements.

HISTORY AND EARLY APL INVOLVEMENT

In November 1973, the Chief of Naval Operations (CNO) published a "Statement of General System Requirements" establishing the need to develop the capability to defend against Anti-Ship Cruise Missiles (ASCMs). As a result, the Navy tasked APL to further refine the concept of dual-mode guidance (passive RF used to point an IR seeker) in a rolling airframe. The Laboratory became the prime contractor with General Dynamics, Pomona Division, as the subcontractor.

APL and General Dynamics conducted demonstrations of the dual-mode concept using the existing Redeye, a 2.75-in.-dia. IR homing missile produced by General Dynamics. The experimental missiles were built using an RF guidance package developed by APL and integrated into the Redeye airframe. A series of firings was conducted demonstrating the validity of the dual-mode guidance concept and the feasibility of a rolling airframe.

As its name indicates, RAM rolls as it flies. The missile must roll during flight because the RF tracking system uses a two-antenna interferometer that can measure phase interference of the electromagnetic wave in one plane only. The rolling interferometer permits the antennas to look at all planes of incoming energy. In addition, because the missile rolls, only one pair of steering canards is required.

The decision was made to transition to a larger airframe to enable broader frequency coverage and enhance lethality. The 5-in. Chaparral Missile was chosen initially, but the Navy later opted to use the Navy-developed Sidewinder airframe for RAM. RAM also uses the Sidewinder warhead, proximity fuze, and rocket motor with only minor modifications to reflect surface-to-air rather than air-to-air use. The guidance and control sections are RAM-developed components.

The original RAM IR seeker assembly had its basis in the Stinger program. Although many of RAM's details are unique, many of its IR seeker components are common with Stinger. In the seeker head assembly, the gyro-optics, reticule, and IR detector are all Stinger-common components. The seeker head itself is from Stinger, with some modifications to make it compatible with the RAM operating environment and mission requirements. The signal processing electronics are identical to Stinger as well, except for the removal of some components to avoid compromising the Stinger IR counter-countermeasures techniques.

PROGRAM STATUS

In May 1975, an operational requirement was issued by the CNO formalizing the need for RAM, and a Program Office was established in the Naval Sea Systems Command (NAVSEA). Today the RAM Program Office is Program Executive Office, Expeditionary Warfare (PMS-472). In the mid-1970s, the German Navy recognized a need for ASCM protection and teamed with the United States in a joint NATO development program. Memoranda of Understanding were agreed to by both countries, culminating in the initiation of full-scale engineering development (FSED) in 1979. At the start of FSED, General Dynamics was selected as the prime contractor for RAM, with German industry support in a subcontractor role; APL assumed the role of technical advisor to the RAM Program Office.

Initial RAM Block 0 development proceeded through FSED and successful operational evaluation, leading to U.S. Navy Fleet deployment in 1993. However, ongoing threat assessments indicated that the RAM GMWS required improvement in order to be capable of engaging non-RF-radiating ASCMs or ASCMs with near-terminal RF seeker turn-on. As a result, the RAM Block I Operational Requirements Document was developed in January 1994 to define the requirements for RAM to engage non-RF-emitting targets. The RAM Block I development objectives include an improved IR seeker with digital processing, implementation of an autonomous infrared (AIR) search and acquisition mode, retention of the existing passive RF guidance capability, retention of resistance to offboard/onboard jammers, and improved performance at low altitude. The IR seeker and IR electronics were the primary portions of the missile to be upgraded. RAM Block I was approved for full-rate production and Fleet deployment in February 2000.

In June 1997, another Operational Requirement Document established the requirement for the RAM GMWS to engage helicopters, aircraft, and small boats. This effort was called the RAM helicopter/aircraft/surface (H.A.S.) mode capability. As with RAM Block I, Bodenseewerk Gerätetechnik GmbH was contracted to design most of the IR seeker software and hardware. This was done in coordination with the prime contractor, Raytheon Missile Systems Company (RMSC), which provided production of most of the missile and design of the IR seeker hardware, guidance software, and all RF hardware and software.

APL INVOLVEMENT IN THE RAM GMWS

As previously noted, APL has been closely associated with the RAM GMWS since its inception, initially designing the RF guidance and acting as technical adviser to the RAM Program Office. The following sections describe some recent APL activities that have been used to support RAM GMWS development, test, evaluation, and integration.

RAM IR Seeker Engineering

Various simulations at the Naval Air Warfare Center, Bodenseewerk Gerätetechnik GmbH, and RMSC are used to support engineering activities for the RAM program. The Computer-In-the-Loop (CIL) simulation at RMSC, however, tests the most complete version of the missile. In addition to being used to integrate software at the system level and evaluate all missile software algorithms, this simulation is used to perform preflight prediction of captive carry scenarios and to support flight tests. In the CIL simulation, background images are incorporated with targets and presented in real time to tactical software. APL, using the Seascape model or the IR measurement system described below, provides many of these background images.

The Laboratory has actively participated in developing and testing the RAM Block I IR seeker. During the early design stages of the seeker, APL assisted in characterizing the noise-equivalent irradiance of the first IR seekers built and continues to support the program through measurement and characterization of the various IR backgrounds that RAM could encounter.

Two captive carry campaigns were conducted during RAM Block I development phases. APL provided target measurement support during the first RAM Block I captive carry exercises using an early version of its Distributed Infrared Imaging Measurement System (DIRIMS). During the next campaign, high-resolution, in-band IR measurements of future H.A.S.-mode targets were collected. Throughout both campaigns, APL also measured the noise-equivalent irradiance of the seeker to confirm consistent performance.

Seascape

Designing and testing IR seekers are complicated processes because the background environment is difficult to simulate and expensive to test. The RAM IR seeker will experience IR backgrounds that usually include the ocean surface (from benign to sun glint), a variable sky condition (from clear to cloudy), other RAM missiles, surface ships, and possibly decoys.

Ocean surface sun glint is extremely difficult to measure, and varying sun angles and sea states create an infinite matrix of testing possibilities. Furthermore, simulation of the ocean surface is complicated and time-consuming. Seascape, a model based on the first principles of wave motion and light transport, was developed to simulate the ocean surface; its use resulted in an innovative, fast method to perform the calculations. Using a tiling technique and distributing the calculations across multiple computers, large high-resolution images are created in a reasonable timeframe. Figure 1 shows an image of the sun glint corridor created with Seascape.

The original Seascape software was implemented using a Perl script to control the distributed array when creating each image. With an objective toward an HTML interface, Seascape was recoded using the Java programming language. The model has been validated by image comparison via statistics and power spectral density; the validation process continues as the model evolves. Recently, additional validation was completed via comparison of the theoretical wave spectrum with measured data.

DIRIMS

To test RAM Block I IR signal processor (IRSP) algorithms, in-band radiometric data on the targets and backgrounds were required. While many of the targets could be simulated using faceted models, IR backgrounds were much more difficult to model. Measured data in the RAM IR band were not available, and field tests performed with the IR seeker on a stationary platform did not tactically represent flight speeds and altitudes.

The design of a new IR measurement system began at APL in 1995. One IR camera on a stationary platform connected to a simple computer interface was used to collect time sequences of the ocean sun glint corridor at Atlantic City, New Jersey, and Virginia Beach, Virginia. These images were then used to test the seeker IRSP and validate the Seascape model. During subsequent field tests, more equipment was added to the measurement system. The resulting DIRIMS was completed in early 1998.

The primary DIRIMS measurement devices are two RAM spectral-band, InSb detector imaging radiometers. The imager with the smaller detector array, 120 × 160 pixels, is used with a 50-mm lens to capture all objects of

Figure 1. Image of the sun glint corridor created using the Seascape model.

interest within a wide field of view. The second, larger detector array (256 × 256 pixels) optimizes the use of a 300-mm lens to measure with 0.1-mrad spatial resolution. Figure 2 shows data taken using the DIRIMS.

RAM Launcher Alignment Canister

The RAM Block I GMWS requires the RAM launcher to accurately point to the true target position in azimuth and elevation. In response to this requirement, the RAM launcher alignment canister (RLAC; Fig. 3), was developed to calculate the end-to-end alignment error of the entire combat system. For example, the Ship Self-Defense System (SSDS) may use a search radar, the Phalanx Close-In Weapon System (CIWS), and ship gyros to calculate the relative bearing and elevation of an incoming target. Incorrect alignment or operation of any piece of the system could result in an unacceptable error in pointing the RAM launcher to that location. This error can be measured using a calibrated boresighted camera installed in an empty RAM canister, a 5-in.-dia. rifled tube used to house and launch a RAM missile in the GMLS. A time-marked record from the camera is used to calculate the target's relative spatial position. The RAM data extraction messages provide information on when and where the launcher is being pointed, and the error between these two positions is the end-to-end pointing error of the system.

The RLAC was first used on the land-based evaluation facility at Wallops Island, Virginia, and then on USS *Gunston Hall* (LSD 44). Throughout RAM Block I developmental/operational testing (DT/OT), APL operated the RLAC during each tracking exercise to ensure that the combat system was within specifications to designate to the RAM GMWS. The canister is also used to check the alignment of RAM-equipped ships in the Fleet.

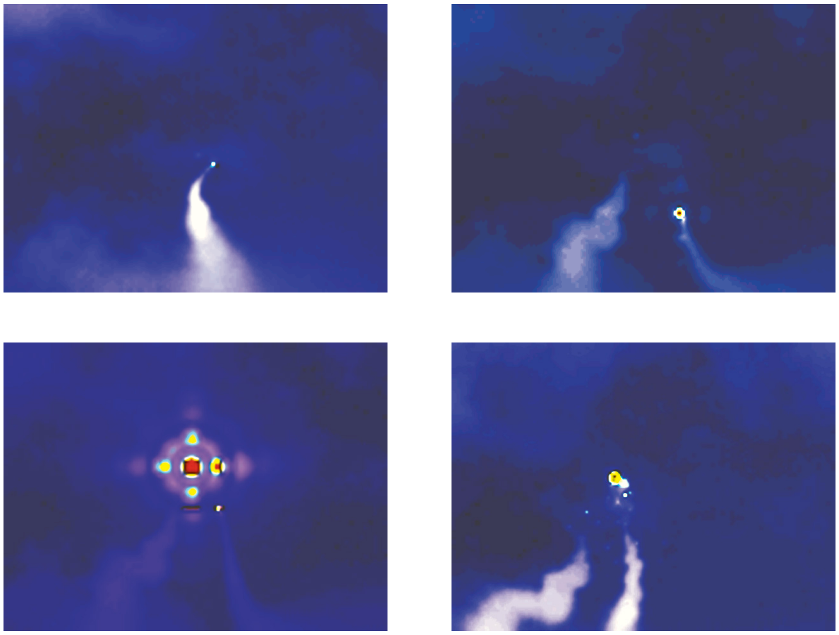

Figure 2. Images from the wide field-of-view imager. Clockwise, starting top left: the first RAM is speeding toward the target, the second RAM is launched toward the target, the first RAM intercepts the target, and debris burns for many seconds after the second RAM intercepts the target.

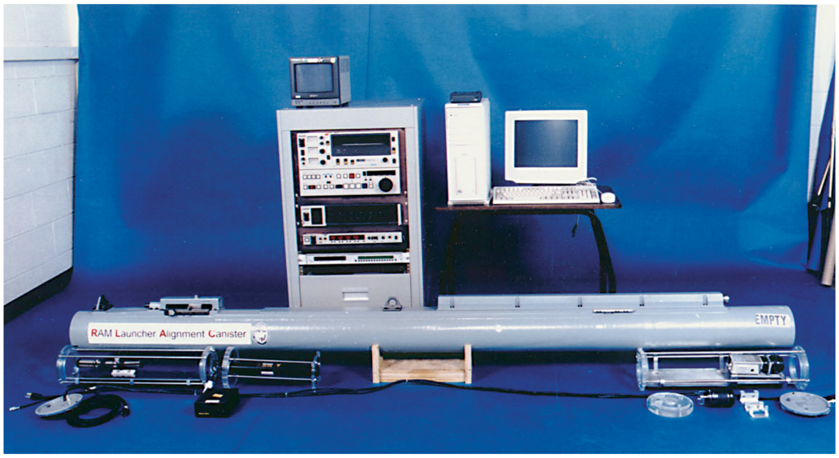

Figure 3. First prototype of the RLAC.

RAM Block I DT/OT Predictive Analyses

The recent RAM Block I operational evaluation (OPEVAL) included a series of live missile engagements conducted on the Self-Defense Test Ship (SDTS). Missile targets included the MM-38 Exocet, AGM-84 Harpoon, MQM-8 Vandal Diver, MQM-8 Vandal ER, and MQM-8 Vandal EER. In support of these tests, APL performed predictive analyses of expected system performance and effectiveness against each of the targets in the test series. While APL was responsible for performance analysis of the SSDS Mk 1 combat system, RMSC was responsible for performance analysis of RAM Block I and depended on APL-predicted launch parameters as input to its simulation.

The predictive analysis for each event included a probability-based, detection-through-engagement sequence including first detection range, firm track range, engagement range, missile designation type, launch range, and intercept range. The RAM designation data included the missile mode (dual or AIR), the IR search pattern shape for AIR-mode designations (circular, seaskimmer circular, or vertical), and the expected target state vector (position and velocity), including estimated statistical variance. Designation error statistics produced from the SSDS Mk 1 RAM custom filter simulation were supplied to RMSC for missile acquisition simulation studies. The RAM custom filter was designed specifically for RAM Block I AIR-mode engagements that require accurate elevation and azimuth pointing. The filter algorithm was incorporated into a Monte Carlo simulation architecture to estimate the pointing accuracy.

Figure 4 shows the simulation architecture used for producing designation error statistics. The target trajectory, radar antenna parameters (beamwidth, antenna height, and frequency), and environmental characteristics (sea state and refractivity profile) are input to the TEMPER (Tropospheric Electromagnetic Parabolic Equation Routine) propagation model to produce propagation factor data over the trajectory. These data are then input to the radar models to produce probability of detection versus range and probability of firm track versus range statistics. Given these data, a measurement sequence is generated and used in a Monte Carlo process to estimate track state errors (position and velocity) versus range. This is done for both the SSDS normal composite tracking filter and the RAM custom filter. The statistics generated from the SSDS normal composite filter are used as input to the CIWS track acquisition model.

The firm track predictions were analyzed with respect to SDSS Mk 1 identification, control, and engage functions. Knowledge of the SSDS track formation, engagement, and sensor contributions was critical for successful testing. Items of particular interest included CIWS track acquisition range, AN/SPS-49 elevation estimate accuracy, SSDS mean time between false track estimates, and AN/SLQ-32 RF power indications for the active seeker targets. Statistical estimates for these items were computed before each event to predict the most likely time of missile designation and the quality of the data given to the missile by SSDS before launch.

The TEMPER model was also used to produce energy density estimates received at the ship for those targets with active RF seekers. The power of the target seeker measured at the ship must pass a minimum threshold in order for RAM Block I to be fired in dual mode. Figure 5 shows the influence of the propagation environment on the RF energy radiated by the target as it approaches the ship. Also shown is the large variability in received energy that can be expected depending on the environment. These propagation profiles were input to a Monte Carlo simulation model that includes the AN/SLQ-32 electronic surveillance measure (ESM) set's measurement error. The model also includes SSDS filtering algorithms for RAM power-adequate prediction. The outputs of the simulation were combined in a weighted average based on the duct height distribution for that time of year and location to estimate the probability of the received power exceeding the required threshold and, therefore, allowing a dual-mode launch.

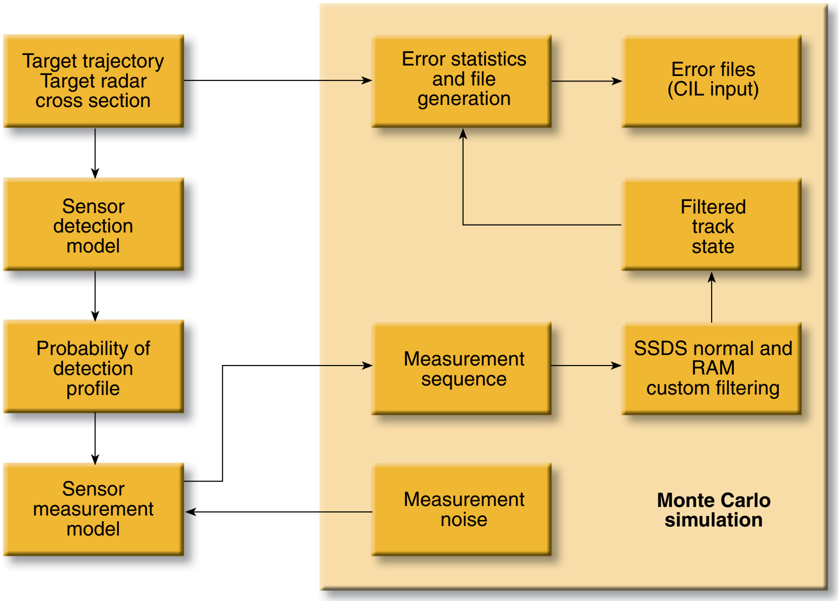

Figure 4. The SSDS filter simulation to produce designation error statistics for RAM.

SSDS Mk 1, RAM Block I Mode Selection

The SSDS Mk 1 currently integrates RAM Block I and is deployed on U.S. Navy LSD 41 class ships. SSDS and RAM together provide a quick-reaction combat capability for non-Aegis-equipped surface ships in the U.S. Navy.

The SSDS Mk 1 system is composed of a computer network and local area network (LAN) access units that integrate sensor and weapon segments. The LAN access units are used to support sensor integration/control and weapon integration/control functions. Situational awareness and combat system command are available through both the Sensor Supervisor and Weapon Supervisor consoles. The SSDS integration and control of sensor and weapon capabilities enable an automatic detect-control-engage capability.

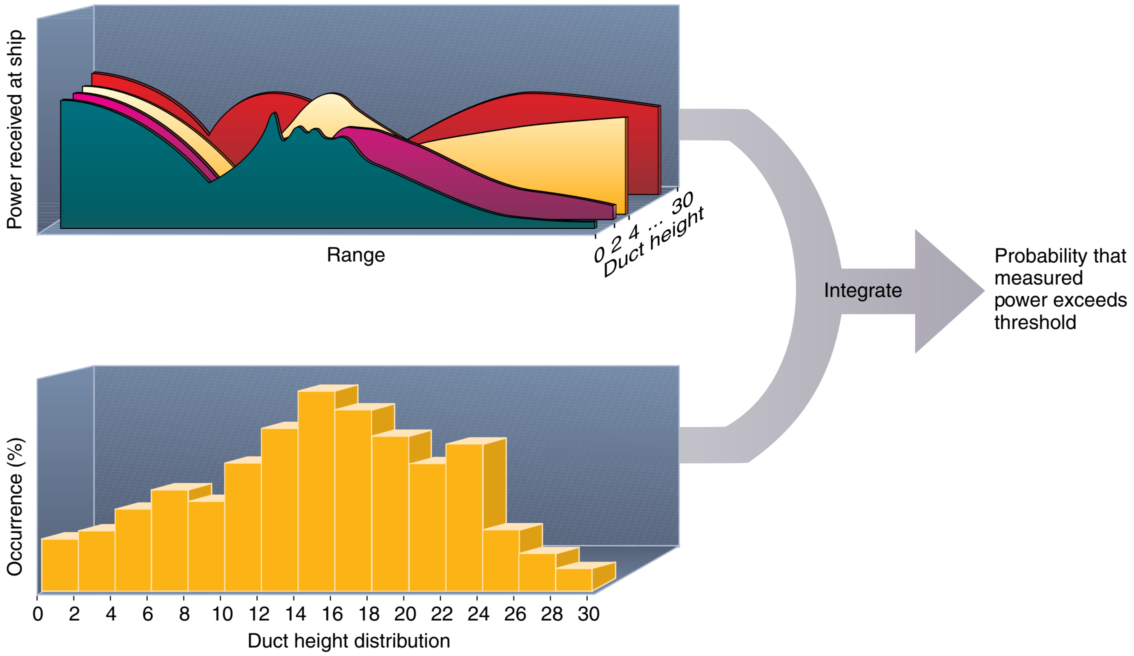

Figure 5. Influence of the propagation environment on power received at the ship.

The sensor and weapon components integrated by SDSS on the LSD 41 class ships include a volume search radar, an ESM set, a surface search radar, the Mk 15 Phalanx CIWS Block IA, and the Mk 31 RAM Block I GMWS.

To decrease the probability of incorrect RAM mode selection, the probability of correctly associating sensor measurements must remain high while the probability of falsely associating them must be minimized. A process of association-resolution was developed to perform this function and characterize the confidence in radar–ESM associations.

Based on data observed during the initial development and deployment of SSDS Mk 1, a false electronic surveillance track identification rate was estimated. This and nominal RAM AIR mode performance estimates were used to determine the optimum resolution bearing gate size. In addition to the radar and electronic surveillance track bearing separation, the reported ESM identification is used to support a kinematics test between the ESM track and the associated radar track. Parameters such as speed, cruise altitude, seeker turn-on range, and maximum range are stored in the SSDS for a variety of current ASCM threats. A radar–ESM association is declared resolved if these compliance tests are successful. If these tests are passed and the measured power of the target seeker is sufficient, dual mode can be selected.

During RAM Block I DT/OT on the SDTS in 1998 and 1999, RF-emitting and non-RF-emitting targets were successfully engaged with SSDS Mk 1 using the upgraded association logic.

Combat System Analysis for the RAM H.A.S. Mode

The RAM Mk 31 Mod 1 GMWS and the RAM Block I missile will receive software upgrades to enable the H.A.S. mode. This mode will take advantage of the existing RAM Block I AIR-mode capability to allow H.A.S. target acquisition and guidance on IR energy alone. RMSC has been developing a design that incorporates horizontal and vertical IR search pattern capability, as well as lead angle logic, in order to engage these crossing-type targets. APL performed combat system analysis to determine the viability of integrating RAM with its search pattern and lead angle selection logic since the algorithms require combat system–generated target track data.

The SSDS Mk 2 to be deployed on select CVNs, LPDs, and LHDs will integrate with the RAM Block I H.A.S. capability. The SSDS Mk 1 deployed on LSD 41/49 class ships was originally intended to integrate the RAM H.A.S. mode, but this is no longer planned. The SSDS Mk 2 design must take into account the RAM modification that includes software changes allowing for the selection of a horizontal IR search pattern. A new search pattern selection table (SPST) will replace the existing table and will contain guidelines for effective IR search pattern selection. Figure 6 shows the proposed architecture for the RAM H.A.S. integration into SSDS based on the architecture of the successfully integrated RAM Block 0 and SSDS Mk 1 systems on LSD 41 class ships. This architecture allows multiple customized RAM pointing filters designed specifically to engage missile and H.A.S. targets. Furthermore, the

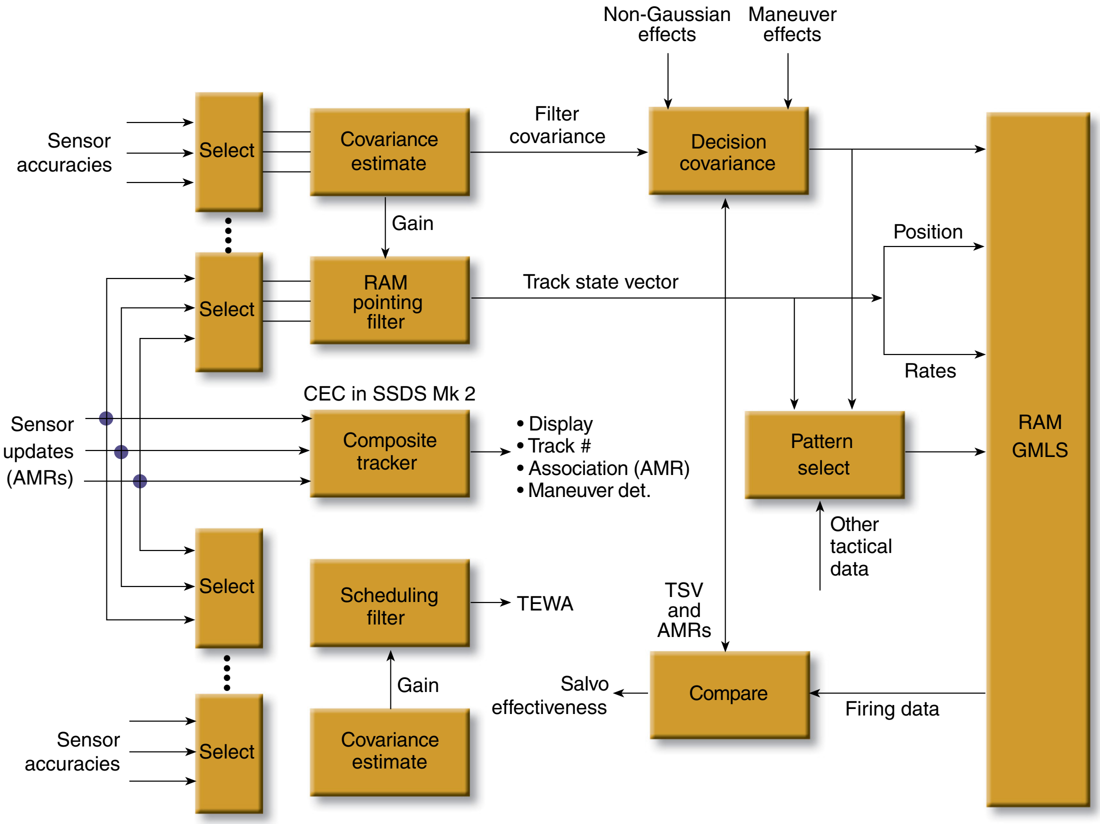

Figure 6. SSDS and RAM GMLS integration (AMR = associated measurement reports, TEWA = threat evaluation and weapon assignment, TSV = track state vector).

specifics of the targets, sensor set, combat system functions, and RAM parameters can be taken into account in the engagement solution.

The current RAM GMWS design allows the integrating combat system to select the IR search pattern based on target elevation uncertainty and bearing uncertainty. This is accomplished through the SPST specified in the Interface Design Specification for the External Designation System (EDS) and RAM.

To support RMSC in its SPST design effort, APL performed combat system studies to show the SSDS filter response, specifically the closest point of approach (CPA) estimation for the H.A.S. target set. The study of U.S. ships was limited to those ship classes intended to integrate the RAM Block I missile, and a typical sensor set from each class was considered. Monte Carlo analysis was performed using these sensor sets and a H.A.S. target set with various speeds and cross ranges.

An SSDS filter simulation was used to model sensor output and combat system filtering. Figure 7 shows a filter comparison plot of CPA error versus range for some typical H.A.S. target scenarios. These data are used to determine the viability of the proposed SPST when integrated with SSDS. Predictably, the estimates of target CPA are not accurate for maneuvering targets and even less accurate with lower gain filtering.

Refinements to the search pattern selection algorithms were recommended to account for target maneuvers resulting in filter lag and to account for other systematic errors specific to the characteristics of the combat system sensors and track state estimate algorithms. Figure 8 outlines the proposed alternative strategy selection based on target and missile quantities including target state estimate, target state uncertainty, systematic error estimation, a maneuver indication

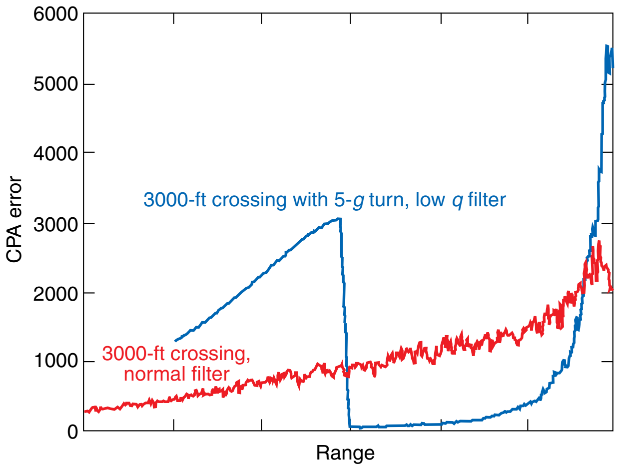

Figure 7. Filter comparison plot of CPA error versus range.

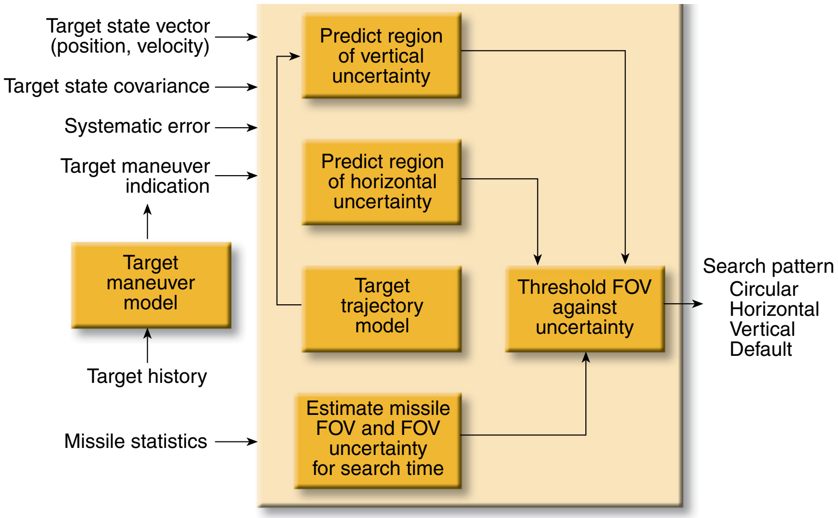

Figure 8. Proposed IR search pattern selection architecture (performance of the target trajectory model depends on trajectory assumptions).

process, “other” tactical data such as doctrine input, and the RAM IR search pattern parameters.

Prototype algorithms for RAM H.A.S. IR search pattern selection and lead angle computation were developed at APL based on the proposed architecture and were recommended to the sponsor and RMSC as an upgrade to the existing design. Figure 9 illustrates a simplified description of the proposed algorithm for lead angle and IR search pattern sizing. The algorithms predict target state elevation and azimuth, including uncertainties into the future before RAM launch, and formulate the expected position of the target relative to the in-flight RAM. This prediction is done under one of two hypotheses, i.e., that the target does or does not maneuver toward the ship. The search pattern shape selection is based on the geometry of the target flight relative to the RAM flight, and the sizes of the pattern and lead angle are based on the field of view needed to cover the nonmaneuvering and maneuvering hypotheses.

RAM GMWS Integration

APL has provided technical assistance to the RAM Program Office through participation in various design reviews (e.g., system requirement review, preliminary design

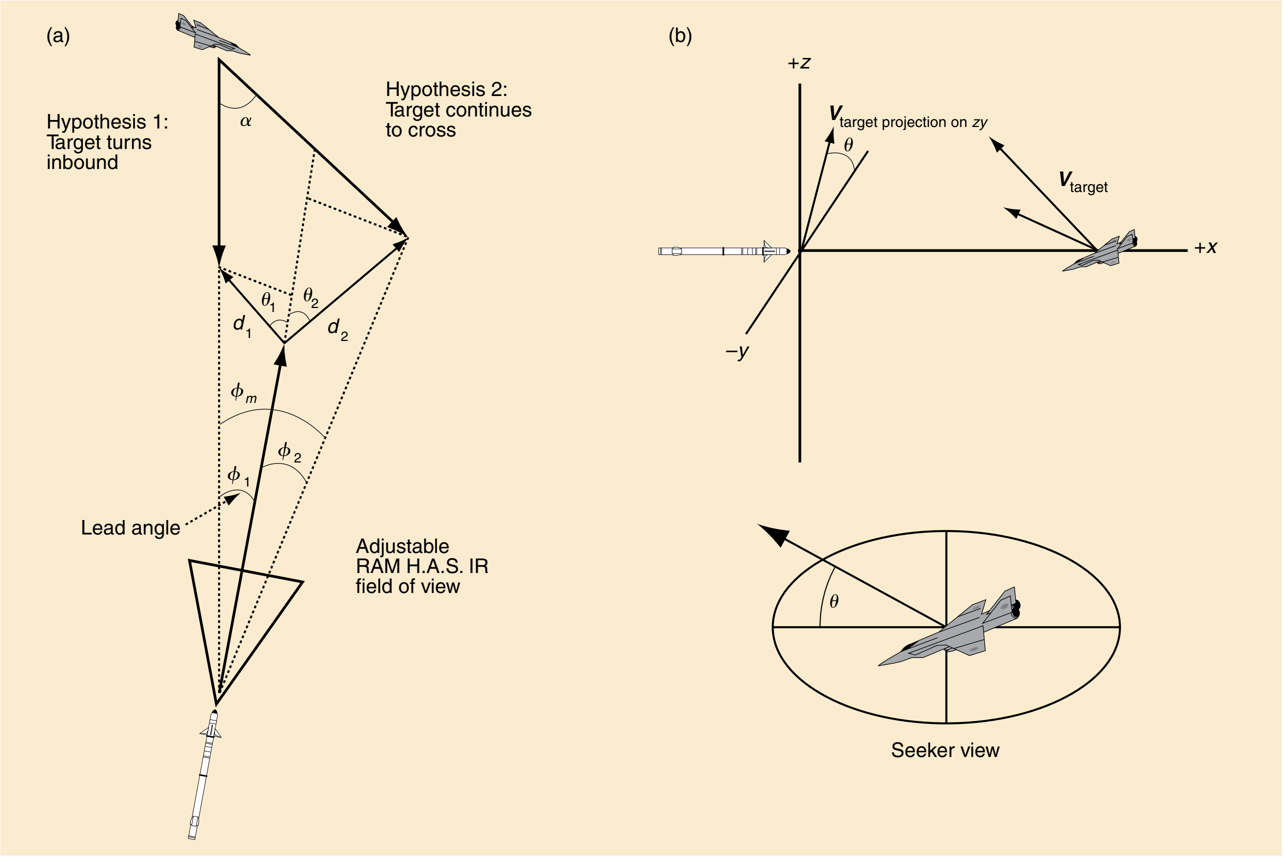

Figure 9. Simplified lead angle (a) and IR search pattern selection algorithm (b). Pattern size is symmetrical and is centered on missile heading vector; therefore, pattern size will be $2\theta_1$ or $2\theta_2$. Minimum pattern is selected when $\theta_1 = \theta_2$ (desired for fast target acquisition). Pattern shape is based on seeker view of predicted target trajectory.

review, critical design review) and working groups on tactical assessment, integration, doctrine, technical exchange, weapon specification, and simulation. Over the years, APL has contributed to the development of various documents, e.g., OP 3594, volumes 8A and 11, which have served onboard as baseline references for the capabilities and limitations of the AN/SWY-3 and AN/SWY-2 combat systems, respectively. They are intended for use by training commands as well.

APL has also provided systems engineering support for the integration of the RAM GMWS with SSDS, AN/SWY-2, and AN/SWY-3 combat systems. For example, the Laboratory led a collaborative, multi-organizational, multi-national effort to develop the Interface Design Specification for EDS and RAM, WS 19622B. This document defines and describes the data exchange and electrical interface between EDS and the RAM GMWS Mod 1.

Other documents to which APL provides input in support of RAM development and integration include RAM GMWS and GMLS specifications, the RAM Guided Missile Round Specification, RAM Tactical Memorandum (TACMEMO), SSDS/SLQ-32 Interface Requirement Specification, AN/SLQ-32 System Requirement Specification, and SSDS/SLQ-32 Interface Design Specification.

SUMMARY

APL has been closely associated with the RAM GMWS since its inception, initially designing the RF guidance and acting as technical adviser to the RAM Program Office. Most recently, the Laboratory has been involved in the development and testing of the RAM Block I IR seeker and supported live missile engagement testing conducted from the SDTS. Through the years APL has also recommended numerous changes to RAM engagement doctrines, firing doctrines, designation logics, and radar–ESM association logics that reside in the external designation systems to ensure the success of the integrated combat system and, in turn, successful RAM engagements.

APL has brought a systems engineering approach to the analyses performed in support of RAM GMWS development and the integration of the RAM GMWS with the AN/SWY-2, AN/SWY-3, and SSDS combat systems. The result of this approach is reflected in the success rate described in the Introduction.

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